AN ATTEMPT TO ILLUSTRATE SOME OF THE PRIMARY LAWS OF MECHANICAL EVOLUTION.

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The object of the present communication is mainly to exhibit a piece of apparatus intended to illustrate, in a concrete form, the operation of certain physical forces in the production of a body which approximates the form of that of certain free-swimming monads. While the necessity for such experiments has been apparent to me for several years, in order to test certain *á priori* conclusions arrived at in the contemplation of the morphological data in our possession in respect to the Protozoa, the difficulty in the way of their trial was the contrivance of the proper kind of apparatus. After a number of fruitless experiments, which it is needless to describe, a very simple form of apparatus was found successful. This device is now described and figured. It serves to show some of the apparent conditions under which a heavy fluid, with a certain specific viscosity or cohesiveness, may, when made to fall through another highly viscous fluid medium, so alter the shape of the former, when in large drops, as to assume somewhat the figure of certain living monadiform organisms.

Certain *á priori* reasons had long existed in the writer's mind to suggest these experiments, and, it may be added, the remarkable experimental results obtained by Plateau, Quincke, Roux, Berthold and Bütschli, in allied fields of inquiry, only served to quicken his interest in what had always seemed worth attempting, but which, for want of the proper means, had hitherto eluded the application of direct experimental verification.

The problem may be thus stated: It was assumed that living matter is viscous, and exhibits a less prompt capacity to change its form than water, when in the form of drops. The plasmodia of Myxomycetes, and the behavior of various amœboid forms, illustrate this part of our statement. It was further assumed that the primæval forms of living things were more or less markedly monadiform, as is shown by the flagellula stage of *Protomyxa*, as well as the male or primordial condition[1] of the germs of the great majority of all multicellular types, and the shapes of the lowest existing forms. Water itself is a fluid body with a certain degree of

[1] The origin of sex through cumulative integration, etc. Proc. Am. Philos. Soc., XXVIII, 1890, pp. 109–159.

viscosity. We have, then, in the motion of the simplest of organisms, the apparent condition of a viscous body, propelled by an energy generated within its own substance, acting as a moving force, and driving it through a less viscous fluid—water.

The application of energy, as a moving force to a viscous and fluid body moving through water or other fluid, was the difficulty which was confronted from the first. Even with the precautions which have been taken, it may be that in the present experiment serious defects of method may have been overlooked. However, the way in which the initial moving force was obtained was simply to use the gravity of the heavier body to propel it through the viscous medium, and to watch and see what the result would be. It was assumed that the conditions as subsisting between the lowest living matter and its medium, water, could be in a considerable degree approximated, and it was confidently expected that there would be certain definite changes of figure which could be predicted as following from the inter-action of the motion of large drops of a heavy fluid moving through a viscous medium, both being homogeneous. These expectations were realized, so far as is illustrated by the apparatus here described.

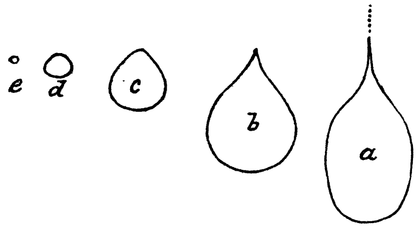
The expectation was, reasoning from cause to effect, that drops of the heavier fluid, moving under the influence of gravity, at a certain velocity, through a viscous medium, would be drawn out at least into an oval or oblong figure, such as is met with in certain protozoa. The actual experiment, however, showed in addition, that if a heavy fluid, such as mercury, was used, and allowed to drop through a very thick, syrupy solution of silicate of soda or soluble glass, enclosed in a test-tube, the drops of mercury, if large enough to fall with sufficient velocity, were not only elongated in the direction in which they fell, but were also drawn out at the upper pole, or that opposite the direction of motion, so that the whole drop rudely simulated the figure of a monad with a single posterior flagellum or tail. While such an artificial form, produced as the consequence of the definite interaction of certain forces, such as resistance, cohesion and friction, generated between two substances of known qualities, cannot, of course, fail to be suggestive, the writer does not mean to imply that the problem of the genesis of the figures or shapes of all monadiform organism is thus solved. It is only in the way of a suggestion toward rendering palpable the action of some of the forces of nature, which have had to do with giving a definite form to some of the lowest and most numerous of

living beings, that the experiment was undertaken. If previous experiments of the writer had utterly failed, there was no reason why, by varying the conditions and means used, that some interesting results should not be obtained, as the sequel proves.

Berthold has conclusively shown that a mass of plasma, such as is found in an amœba, would, for physical reasons, tend to be elongated in the direction of its own motion, such as is actually observed to be the case. The experiment with the large drop of mercury falling through a thick solution of soluble glass, shows that if the friction and cohesion incident to its motion be the same on all sides, and sufficiently great, that the whole mass, instead of flattening in one direction and elongating in another, as in the case of an amœba creeping over a fixed substratum, there is a general elongation in the direction of motion, resulting in the production of an elongated or pyriform body with a short but sharply attenuated flagellum or tail. The flagellum seems to be largely, though probably not wholly, the result of friction, since at its apex the mercury is continually being pulled off in the form of almost impalpably fine globules, so that in this way the large drop may be slowly disintegrated into a vast number of minute metallic globules.

That the figures of many of the lower organisms are affected more or less by such forces as those of cohesion and friction with the circumjacent fluid media in which they live, and by surface-tension, etc., there can scarcely be any doubt. In what ways these forces tend to modify organisms can only be determined by the most laborious and difficult methods of observation and study. Such effects cannot be determined by studying the dead organisms, but must be conducted on the living material, with the help of a great array of comparative measurements taken during active movement and rest.

The experiment here described, and which is represented on a reduced scale of one-half in the accompanying figure, shows a number of interesting facts. If the drops are below a certain size they are spherical; if somewhat larger they are flattened in the direction of motion; if still larger, the drops assume the singular monadiform-shape already described. With these three forms and sizes of drops or metallic



globules there is associated a progressive acceleration of motion due to the gradually increased gravity of the individual drops, and consequently increased friction and cohesion of the larger surface of the larger drops with the viscous medium through which they fall. If the attempt were made to represent the law according to which the three forms of drops were produced, it would be necessary to determine the weight or mass of each of the three sizes of drops or globules of mercury, and their rate of motion in a given interval of time. The factors of friction and cohesion would be dependent upon the increase in the area of the surfaces of the three grades of drops. The viscosity of the medium would be the same for all three sizes. These data are measurable, and could be expressed in mathematical formulæ.

The writer is aware that this experiment does not account for flagella at both ends of a monad, such as many bacterial forms show; nor does it account for the genesis of cilia or pseudopods all over a Protozoan, or for the cilia on an epithelium lining a cavity, or covering a free surface in one of the higher Metazoa. It is presented only with a view to indicate that experiment in the direction of the artificial simulation of some of the lowest living forms was not without much that is suggestive, even though no definite conclusion could be formulated from such an experiment, except the single one, that the nature, and especially the velocity of the motions of the lowest organisms, through their fluid surroundings, has probably had a definite or determinate influence in modifying their shapes so as to develop a major axis. Or where, as in some cases, the body of the monad is attached to the side of a long vibratile flagellum, there is an evident tendency to drag out or lengthen the monad's body in the direction of motion. The resemblance of the flagellula stage of *Protomyxa* to our large artificially-produced monadiform drop of mercury moving in a solution of soluble glass is even more striking.

Furthermore, as a matter of fact, we find, as in *Paramœcium*, that a slight spiral torsion of the body causes such a form to rotate while moving in a linear direction, and conformably with its major axis or longest diameter.

There is, in fact, no evidence to disprove that the major axis of all lower forms, as well as the major axes of higher forms, may not have been at first partly or wholly the result of the direct interaction of their primitive ancestral types with their surroundings.

In this connection, I may mention the planulæ of Coelenterata, which are elongated in the direction of their own motions, as well as the gastrulæ of sponges and the lowest vertebrates, which are similarly extended in the direction of their principal motions. That such tendencies of configuration were thus, in the first instance, directly adaptive or directly acquired, there is the greatest probability. Their subsequent transmission through inheritance by unequal growth along the major and minor axes is equally probable, in that the unequal growth may have been in the first place unequally stimulated along these axes by variation of stress along them, due to the motion of the organism itself. For stress or resistance from without, along the longest axis would be less than in the direction of the minor axis, which would constantly tend to be compressed, as the experiments here described testify. There are even facts which support this conclusion in another way. For example, the wild trout has a sharper head and more slender body than the trout reared in ponds and basins under domestication, and the same rule holds in respect of gold-fishes. The correlation of a sharper head and slenderer body is evidently with greater activity and ease of motion, so that the wild form may be regarded as "clipper-built," or like the figure of the famous yacht "Puritan," as compared with an ordinary fair-sailing sloop. These correlations of figure, with proportional powers of motion, are even more marked amongst the families of fishes themselves. The swiftly-swimming sharks, mackerel and herring are the "clipper-built" fishes of the seas; while the slow *Mola*, or sun-fish, typifies the living but helpless "hulk" sometimes run down and killed by actual collision with vessels.

It also seems to be a universal law of animal motion, that its direction in free forms is in conformity with the major axis or greatest diameter of an organism, or in the direction of least resistance. A cross-section somewhere at right angles to the greatest diameter gives the minor axis. This minor axis interposes the least resistance to motion in a fluid medium. It is also true that the waves of undulatory, vermicular, or vibratory motions always conform in direction to the major axis of an organism. In the simplest form studied by the writer, viz., that occurring in the movements of *Trypanosoma Balbiani*, the intestinal parasite of the oyster, this undulatory motion is propagated alternately from opposite ends of the fusiform body of the animal. The result is that

the direction of the motions of the creature are reversed as often as the direction of the vibrations or undulations of the body is reversed, as must result from the well-known laws of wave-motion.

The assumption of the undulatory or vibratory method of locomotion, according to the laws of wave-motion, as in fishes, entails the necessary conformity of the longest or major axis with the direction of motion. No other direction of progressive motion following from the undulations of an elongated body is conceivable, as seen in the case of *Trypanosoma*. The direction of the motions of a vast majority of animals is therefore determined according to the physical laws, the operations of which we have just been tracing, while it has been equally well shown in the experiment presented that an energy, generated within the organisms, and dissipated in the form of motion, must always tend to elongate such an organism moving in a fluid, in conformity with the well-known laws of friction and cohesion, to which a soft, viscous, primitive organism must have been exposed during its motions through such a fluid medium.

The energy expended in molar or mass-motion was, therefore, partly dissipated at one time in giving a figure to the organism, as follows from known and empirically demonstrable laws of the motion of viscous bodies in fluids. We may, therefore, literally assert, with Lamarck, that organisms have, through their own motions, tended to shape and modify themselves. And it may be added, there is no evidence at present to show that such laws dominating similar forces are not active at the present moment, and that mechanical evolution is now in progress. The Lamarckian and Darwinian hypotheses are therefore reconcilable with the doctrine of the conservation of energy—the so-called Neo-Darwinian doctrine is not, and is therefore false. The first-named hypotheses thus lend themselves to an explanation of the genesis of variations which the latter does not, since its most strongly-expressed tenet is that acquired characters cannot be inherited. (Acquired only as here supposed, viz., through the expenditure of energy.)

Another effect of the undulatory motion of living bodies, along their major axes, is, that if they move freely in a dense medium, such as water, they tend to be flattened, especially at the ends, and at right angles to the plane in which the undulatory or wave-motions of the body are propagated. This is seen first of all in monadiform organisms themselves, and their flagella or propelling organs, which are flattened, as is shown by successful cross-sections

of such minute structures. This lateral flattening, due to lateral undulatory motion, is also illustrated by the Hydrophidæ amongst snakes, in which their marine swimming habits have developed a vertically-flattened tail in a series of types which are ancestrally allied to land forms amongst the Elapidæ. It is further illustrated in fishes in which the flattening has expressed itself in the development of vertical fin-folds and fins. In *Sagitta*, where the undulations of the body are in a vertical plane, and not lateral, as in fishes, the fins are flattened horizontally.

The further consequences of this process, under the stress of still further modifying conditions, may be traced in the origin of heterocercy in fishes, as may be illustrated by means of a paper model vibrated from side to side in a dish of water. If the lower caudal lobe is widened, as it probably was by energetic sculling strokes of the tail in struggling to get to the surface, there must result an upward flexure of the axis of the tail, resulting in the morphological complication seen to-day in diverse groups of fishes which have no possible genetic connection with each other, as is proved by the structure of the tails of these several forms. Since there cannot be any possible genetic connection between Selachians and Teleostomes, or of the latter with the sturgeons or Chimæroids, the heterocercal conditions of these forms must have arisen independently, and as a consequence of the same physical causes acting independently and in the same way for each group.[1] The fracture of the caudal rays of the Salmonoids and Clupeoids follows conformably with the laws of the undulations of the tail in a dense medium.[2]

Still other consequences of motion in differentiating structure may be traced, such as the correspondence of the number of muscle-plates with the number of vertical rows of scales, as I have lately found in certain Clupeoids. This is also true of the vertebral column and the vertebral centra, whose biconcave bodies in lower types are a marvellous expedient, rendering continuous growth and concomitant functional activity possible. Their form has not the remotest relation to any arrangement for strength to be compared with the trusses and beams of a system of cantilevers, as absurdly

1 On the Morphology and Evolution of the Tails of Osseous Fishes. Proc. Am. Ass. Adv. of Science, XXXIII, 1884, pp. 532, 533.

2 Proofs of the effects of habitual use in the modification of animal organisms Proc. Am. Philos. Soc., XXVI, 1889.

suggested by Prof. Bardeleben.[1] Notwithstanding their biconcavity, the vertebræ of the salmon show undoubted evidence of conforming to the shape demanded of them in executing the lateral undulatory movements of the body. In the Cetacea, where these undulations are vertical, the conformation of the caudual vertebræ is precisely the reverse of what it is in the salmon.

Farther research will undoubtedly disclose farther evidence of the forward displacement of the vertical and paired fins of fishes. This displacement may, with absolute certainty, be traced to the manner in which the vertical fins exercise their functions in certain instances, as in *Mola*, for example.[2] The continuous tension forwards on the bases of the dorsal and anal fins, acting like propeller-blades from before backwards, has conspired to produce such a result only too plainly evident in a study of the skeleton. But even this result is to be traced to antecedent modes of motion of the whole body, which were undulatory in character, but which now no longer affect the body itself of this singularly-modified fish. We may, therefore, affirm, that habits, and ultimately functions, have been superposed, leading to the superposition of structures. If this method of procedure is philosophical, the whole fabric of morphological method and speculation now rife amongst biologists must be re-cast. For my own part, I have no hesitation in declaring that some of the current methods are destined to end in disappointment. The method is overweighted with morphological details, which have nothing but a morphological significance in the eyes of this newer school of biologists. What such methods may lead to is indicated by papers which have appeared within the year on the origin of vertebrates from crabs and scorpions!

No hypothesis of the origin of the limbs yet offered is anything but purely morphological, and by so much is one-sided and defective. None of the hypotheses of the evolution of the limbs link the palpable facts of structure with the palpable facts of function, and, above all, with the mechanical and physiological laws, in the widest sense, which that function and structure illustrate. As long as they do nothing more, these hypotheses are a mere conning of data to which no significance can or will be attached by those who ask for more than mere anatomy, except as those data help to illustrate

[1] Beiträge zur Anatomie der Wirbelsäule, 4to, Jena, 1874. (Die Wirbelsäule als Fachwerk, pp. 20–27.)

[2] The Swimming Habits of the Sun-fish, Science VI, 1885, pp. 103–104.

a philosophy of that science whose barest outlines have scarcely more than been indicated. We may truly say, with Roux, that there is an anatomical discipline of the future which has scarcely yet been developed even in outline. Only here and there has any one been bold enough to declare himself. This new science will not grow as fast as morphology. It will require a different sort of mental equipment than is possessed by the majority of morphologists, most of whom seem to be lost in trivial morphological details, or in framing systems of relations and phylogenies based on purely morphological data, and which are more or less happy and valuable as aids in identifying forms. This newer discipline will demand that a structure be turned over and looked at from every conceivable standpoint of conditions which have had to do with its genesis. The method is infinitely slow, because it recognizes the fact that *structures, functions* and *conditions* are contemporaneous or superposed; and to unravel the method of the working of the energy of life as manifested to us in living creatures, through this interwoven trinity of factors, is its object.